1D AND 2D FULL-WAVE SIMULATIONS OF O-MODE REFLECTOMETRY EXPERIMENTS IN THE PRESENCE OF NON-COHERENT FLUCTUATIONS

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I. Introduction

The understanding of turbulent phenomena in fusion plasmas is a key problem for the future generation of tokamaks. Combining high spatial and temporal resolutions, reflectometry is an interesting diagnostic for the study of density fluctuations [1]. However, the quantitative interpretation of reflectometry measurements remains difficult due to complex processes affecting the probing wave propagation. In order to facilitate this interpretation, various theoretical and numerical studies have been already carried out but most of them have been limited to the case of fixed-frequency reflectometry and coherent density fluctuations. We propose here to study the effect of non-coherent density fluctuations (i.e. presenting a large k-spectrum) using 1D and 2D full-wave O-mode codes [2]. First results obtained from a simply model of non-coherent density fluctuations in fixed as well as in broadband frequency reflectometry are presented. The similarity with experimental results shows the potentialities of this model to reproduce important features of turbulence.

II. Model of density fluctuations

Turbulent phenomena in tokamaks induce density fluctuations that are superimposed to the average density profile. In the 2D case, the density profile can be then written as follows:

$$n_e(x,y) = \langle n_e(x,y) \rangle + \delta n_e(x,y)$$

where x and y are respectively radial and poloidal coordinates. Turbulence measurements performed in Tore Supra have shown that the density fluctuations present k-spectrum components until 10 - 20 cm^{-1} [3]. Then we assume that the density fluctuations can be decomposed as Fourier series:

$$\delta n_e(x,y) = \sum_{k_x=-n}^{+n} \sum_{k_y=-m}^{+m} a(k_x,k_y)\cos\big(k_x x + k_y y + \varphi(k_x,k_y)\big)$$

where k_x and k_y represent the radial and poloidal components of the spectrum and $\varphi(k_x,k_y)$ is a random phase. The amplitude spectrum $S(k_x,k_y)$ of density fluctuations is thus defined by the coefficients $a(k_x,k_y)$. Depending on the random choice of the phase terms $\varphi(k_x,k_y)$, we can note that an infinity of solutions for the density fluctuations gives the same spectrum. Consequently, the study of the effect of a given fluctuation spectrum should require a large number of cases to get a statistical response. A displacement of the density fluctuations with respect to time (for instance to simulate the poloidal rotation of the turbulence) can also be simulated by the code. Just note that the spectrum changes in the presence of a velocity shear. In the results depicted in the following, an experimental-like spectrum [3] (i.e. plateau for $k < 4$ cm^{-1} and k^{-3} decreasing for 4 $cm^{-1} < k <$ 15 cm^{-1}) has been input in our code.

III. Broadband frequency reflectometry simulation

Simulation of broadband reflectometry experiments where frequency sweeping time ≥ 20 µs imposes a large number of iterations resulting in long computing times for 2D codes. From 1D simulations we show in the case of a frozen density profile that a shorter sweeping time can be used without any significant effect on the phase of the reflected signal. This is illustrated on figure 1 for two different sweeping times (20 µs and 50 ns) in the presence of a high level of turbulence (10% normalized to the maximum density). The amplitude of the reflected signal presents large variations for the short sweeping time (50 ns) whereas it is almost unperturbed for a sweeping time of 20 µs. However, we can notice that the group delay profile determined from a sliding normalised FFT technique remains surprisingly identical whatever the sweeping time. Consequently, we use in the following 2D simulations a sweeping time of 50 ns assuming that it remains relevant to study the fluctuation effects on the time of flight (but not on the amplitude of reflected signal). Further analysis on the limit for sweeping time reduction can be found in [4].

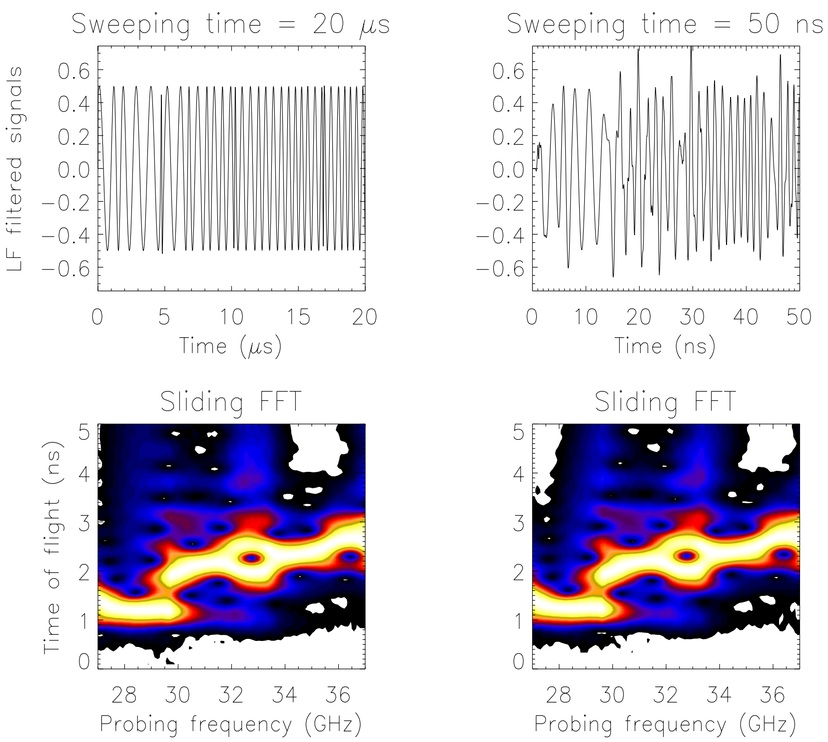


Figure 1: Low frequency filtered signals (top) from 1D code and corresponding sliding FFT curves (bottom) in the presence of non-coherent density fluctuations (level of 10%)

We present now 2D simulations in the presence of frozen density fluctuations, obtained from the model detailed in section II. On figure 2 contour plots of the electric field (at a given time during the frequency sweeping) without density fluctuations and in the presence of density fluctuations with a level of 10% are compared, showing the wave scattering induced by such fluctuations. The effect on the time of

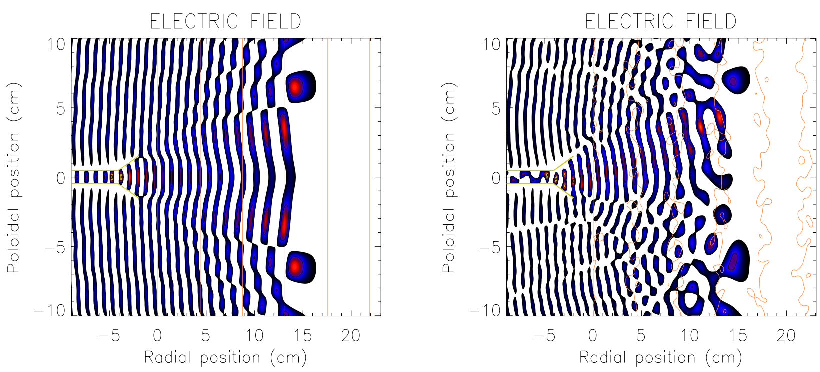


Figure 2: Electric field contour plot from 2D code without density fluctuation (on left) and in the presence of non-coherent density fluctuations with level of 10% (on right)

flight is exemplified on figure 3 where a comparative study is made for density fluctuations of 3 %, 5 % and 10 %. In each case, 5 random choices of phase values needed to define the density fluctuations (see section II) have been considered. The perturbations remain small for 3 % (0.1 - 0.2 ns) and will not affect significantly the profile reconstruction. For a level of 10%, the time of flight perturbations can be extremely strong (until 1 ns) which will prevent the correct density profile reconstruction.

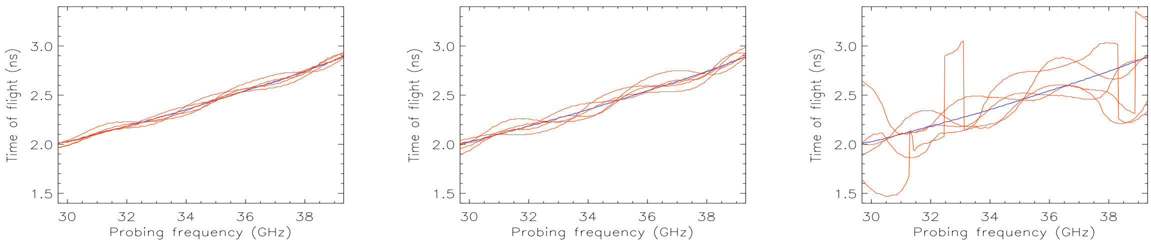


Figure 3: Perturbations on the time of flight in the presence of non-coherent density fluctuations (respectively for 3, 5 and 10 %)

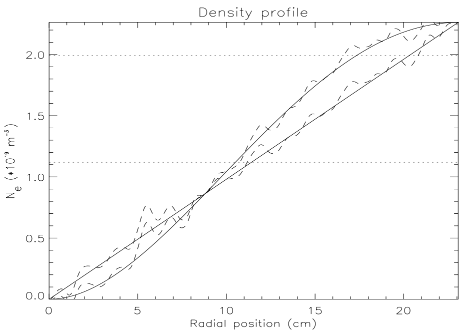


Figure 4: Linear and peaked density profiles with superposition of the same density fluctuations (The two vertical lines represent the probed region)

A reduction of the reflectometry signal perturbations is generally noticed during improved confinement regimes (H mode, ITB). Two hypotheses are suggested to explain this reduction, namely a local steepening of the density profile and a modification of the density fluctuation spectrum. We analyse here the effect of the steepening of the density profile. Using the same density fluctuations of 10 %, we made a simulation for two types of density profile (see fig 4). As expected the time of flight profile depicted on figure 5 shows a reduction of the perturbations for the steeper profile, thus confirming the influence of the density gradient on the signal perturbations.

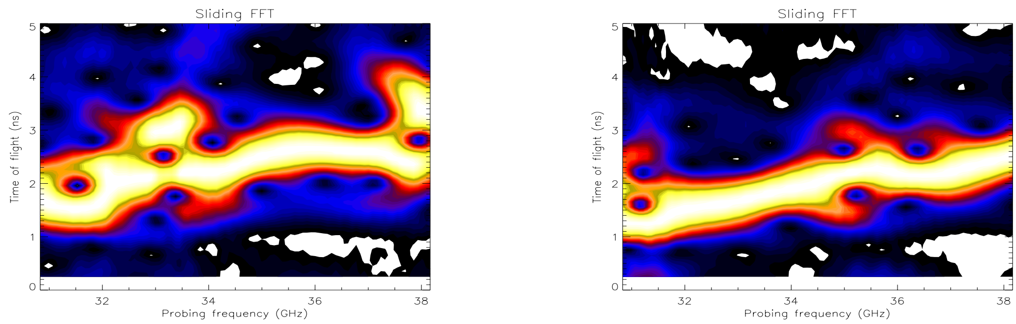
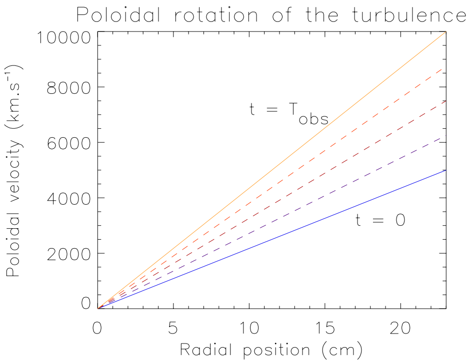


Figure 5: Reduction of time of flight perturbations for steeper profile

IV. Fixed frequency reflectometry simulation

In this section the effect of poloidal rotation of the turbulence in fixed-frequency reflectometry is studied. Simulations in the 2D case are limited by very demanding computing times. As an example, for the numerical box used in these simulations (30 and 20 cm in radial and poloidal directions), the study of wave propagation during 500 ns requires 20 hours of computing time (on PC computer - AMD Athlon 850 MHz – RAM 256 Mb). Thus for reasonable computing times, the time range for physical phenomena study remains generally too small to see significant phenomena occurring in fusion plasmas. For instance, measurements of poloidal rotation of the turbulence suggest velocities in the order of few km.s^{-1} [5]. Observation times at least in μs range should be then considered to study the effect of poloidal rotation. Preliminary results suggest that the rotation velocity can be increased without qualitative change (that must be confirmed with additional simulations). Consequently, in order to reduce the computing time the velocity of turbulence rotation has been largely increased in the following simulation. Simulating the poloidal rotation of the turbulence (5% of amplitude with velocity shear in radial direction), we analyse the reflectometer response when the rotation velocity increases as occurs during the formation of transport barriers (fig 6 on left). As seen in experiments, the spectral analyse of the reflected signal highlights the high frequency shift due to the velocity increasing (fig 6 on right). More simulations should be done in the future to interpret Doppler reflectometry experiments [6].



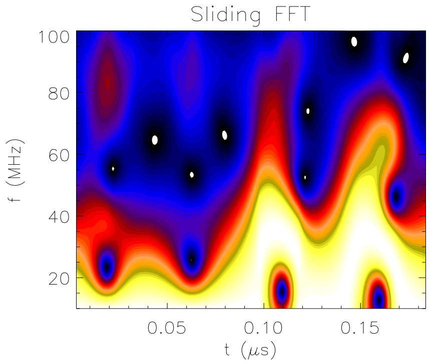


Figure 6: Effect of poloidal rotation of the turbulence on fixed-frequency reflectometry measurements (Note that unrealistic velocities have been considered to reduce the computing time)

V. Conclusion

A simply model of non-coherent density fluctuations has been developed to reproduce important features (k-spectrum in radial and poloidal directions) of turbulence in tokamak plasmas. Preliminary results obtained from full-wave simulations confirm some effects already observed in fixed as well as in broadband frequency reflectometry experiments. First we show that a level of turbulence of 10 % can lead to strong perturbations in the time of flight profile thus preventing the correct density profile reconstruction. Simulations confirm also the role of the steepening of the density profile (as occurs during H mode or ITB) in the reduction of the perturbations of reflected signals. Finally the effect of poloidal rotation of turbulence in fixed frequency reflectometry signals is assessed.

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